A High Inclination Solar Mission Enabled by Near-Term Solar Sail Propulsion

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Abstract

Our current understanding of the Sun, its atmosphere, and the heliosphere is severely limited by a lack of good observations of the Sun's polar regions. A High Inclination Solar Mission (HISM) mission would go into a 0.48-AU circular solar orbit with at least a 60° inclination to conduct long-term observations of the Sun's poles using both situ and remote-sensing instruments to study the connections between the Sun, the solar wind, and solar energetic particle events.

The propulsion requirements to implement HISM are beyond the capability of conventional chemical propulsion and extremely challenging even for highly efficient solar electric propulsion. To enable HISM and a host of other propulsion-intense space science missions, NASA is actively developing solar sail propulsion, capable of continuous low thrust for the extended periods of time required to meet the ΔV requirements of HISM. Upcoming solar sail missions include the Near Earth Asteroid (NEA) Scout (2021 planned launch) and Solar Cruiser (candidate for flight in 2024).

Solar sails use sunlight to propel vehicles through space by reflecting solar photons from a large, highly-reflective sail. This continuous photon pressure provides propellantless thrust, allowing for very high ΔV maneuvers on long-duration, deep-space exploration. Since the Sun supplies the necessary propulsive energy, solar sails require no onboard propellant, thereby potentially increasing useful payload mass.

The NASA MSFC Advanced Concepts Office recently completed a detailed mission concept study of HISM based on the solar sail propulsion technologies being developed for NEA Scout and Solar Cruiser. The HISM spacecraft concept envisions carrying a Doppler & Stokes Imager, a coronagraph, magnetometer, Faraday Cup, a plasma spectrometer, and a radio and plasma wave package to meet the science objectives established for a solar polar orbiting mission in the Heliophysics Decadal Survey. This paper will describe the mission concept and its solar sail propulsion system.

Keywords: Solar Sail, In-Space Propulsion, Solar Science

Acronyms/Abbreviations

Active Mass Translator (AMT)
Astronomical Unit (AU)
Center-of-Mass (CM)
Center-of-Pressure (CP)
Goddard Space Flight Center (GSFC)
High Inclination Solar Mission (HISM)
High Strength Composite (HSC)
Marshall Space Flight Center (MSFC)
National Aeronautics and Space Administration (NASA)
Near Earth Asteroid Scout (NEAS)
Polyimide Embedded Photovoltaics (PE-PV)
Reaction Control System (RCS)
Reaction Wheels (RW)
Reflectivity Control Device (RCD)
Triangular, Rollable, and Collapsible (TRAC)

1. Introduction

Solar sails are large, mirror-like structures made of a lightweight material that reflects sunlight to propel a spacecraft, providing high ΔV for many types of missions. The continuous solar photon pressure provides thrust eliminating the need for the heavy, expendable propellants characteristic of conventional chemical and electric propulsion systems. Solar sails can access many novel orbits by virtue of this unique propulsion method as described and shown in Figure 1.

- By accelerating along the existing velocity vector, the orbital energy of the spacecraft is increased, thereby spiralling it away from the Sun.
- By accelerating opposite to the velocity vector, the orbital energy decreases, spiralling inward toward the sun.

• By accelerating out of the orbital plane, the sail can change inclination.
• By carefully managing attitude control, the sail can perform station-keeping in a desired location near-indefinitely.

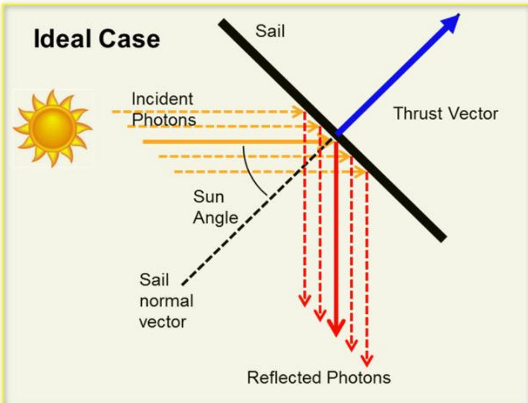

Figure 1. Solar sails, propelled by reflecting sunlight from a flat, thin deployable membrane, may change the net thrust vector by orienting the sail relative to the incident sunlight.

Using an 86 m^2 solar sail, the NASA Near-Earth Asteroid Scout (NEAS) mission will perform reconnaissance of an asteroid, characterizing it for possible future human exploration, and demonstrate the capability of an extremely small spacecraft to do so at a relatively low cost [1]. Based on the solar sail technology developed and flown by the NASA NanoSail-D2 [2], the NEAS mission is funded by NASA's Human Exploration and Operations Mission Directorate (HEOMD) and managed by NASA Marshall Space Flight Center. NEAS will be launched on the first flight of NASA's Space Launch System (SLS) in 2021.

An MSFC-led team (including NASA GSFC, Ball Aerospace, NeXolve, and Roccor, LLC) are completing for the Science Mission Directorate a Phase A Concept Study Report as one of two competitors for flight in 2024 as a secondary payload on the IMAP mission [3]. The 1653m^2 Solar Cruiser sail provides a characteristic acceleration (Ac) of >0.12 mm/s^2. The solar sail architecture uses a quadrant sail design with four composite booms that are deployed from a central rotating deployment mechanism and sail hub. The sail membrane is the space- and sail-proven aluminized CP1 polyimide substrate successfully flown on NanoSail-D2 and to be flown on NEAS. To further advance the solar sail architecture, Solar Cruiser also demonstrates polyimide embedded photovoltaics (PE-PV) to generate power, and attitude control using reflectivity control devices (RCDs) on the sail surface.

The sailcraft system developed to support the HISM mission's science objectives is directly scalable from the Solar Cruiser design without any new technologies or technologies requiring additional in-space demonstration.

The HISM is a concept for an out-of-the-ecliptic mission for observing the Sun and the heliosphere. The mission profile is largely based on the Solar Polar Imager concept [4]; initially spiralling in to a 0.48 AU ecliptic orbit, then increasing the orbital inclination at a rate of 10 degree per year, ultimately reaching a heliographic inclination of >75º.

HISM remote sensing instruments include an imaging spectropolarimeter (Doppler imager / magnetograph) and a visible light coronagraph. The in-situ instruments include a Faraday cup, an ion composition spectrometer, and magnetometers. Plasma wave measurements are made with electrical antennas and high speed magnetometers.

2. Mission Science Objectives

The science goals for HISM meet those described in the National Academy Decadal Survey \Solar and Space Physics: A Science for a Technological Society" [5].

1. Understand the Sun's internal structure and surface dynamics in the polar regions
2. Understand the 3D structure of the Solar/Heliospheric magnetic field and its variation over time
3. Understand the variations in the solar wind speed and composition at high latitudes
4. Understand the origin and acceleration mechanism of solar energetic particles
5. Evaluate the use of high-latitude data for space weather predictions and warnings

Potential instruments to be flown on HISM are listed in here:

- Doppler and Stokes Imager
- Coronagraph
- Magnetometers
- Plasma Spectrometer
- Faraday Cup
- Electric Antenna
- Search Coil Magnetometer

3. Mission Concept

The HISM ground rules and assumptions include:

- Dedicated launch to C3 = 0 trajectory
- Spiral-in to 0:48 AU circular ecliptic orbit, followed by cranking to 75º inclination
- Utilize Solar Cruiser sail technology scaled up to 7000 m^2
- Total mission life of 11 years
- Maximize science observing time

The HISM spacecraft consists of the Science Bus, Lower Bus, sail assembly, and the Spin-up Bus (Figure 2). The sail spins at am ~1 rpm rate to allow centrifugal force to augment the boom stiffness. Attached to the sail is the Spin-up Bus, which contains a propulsion system for attitude control prior to sail deployment and for initiating the sail spin during sail deployment. The Spin-up Bus is jettisoned after the sail is deployed. The Science Bus is a fine-pointing platform containing all science instruments and their electronics, as well as the solar panels. The Lower Bus contains the remaining avionics subsystems, and while it is de-spun (decoupled from the rotating sail through a de-rotation mechanism), it is not required to meet the fine-pointing requirements of the science instruments.

The mass of the sailcraft is estimated between 240 kg and 293 kg including margin, resulting in a sailcraft characteristic acceleration of Ac = 0.265 mm/s^2 or Ac = 0.217 mm/s^2 respectively. The total launch mass is 358 kg, including margin.

The spinning solar sail is a major design constraint, as a spinning platform is unsuitable for remote sensing observations. One possible solution is to start science observations only after the sailcraft has reached the target high-inclination orbit and the sail has been jettisoned. Alternatively, a de-spin mechanism in the sailcraft can allow full science operations while the sail is still attached and spinning. The latter approach was chosen for HISM to maximize science returns by starting observations early in the mission and continuing these observations from different orbital inclinations. This also allows the sailcraft to rely on RCDs for momentum management, eliminating the need for any propulsion system on the sailcraft for desaturating the momentum wheels.

Further, a large deployable structure such as a solar sail cannot be assumed to be perfectly symmetric, and asymmetries may lead to precession of the sail. Therefore the HISM bus design consists of 2 sections: the fine-pointing Science Bus and the Lower Bus, as shown in Figure 2. The Lower Bus is de-spun from the spinning sail through a motorized rotary joint, but is allowed to precess with the sail. The Lower Bus contains the sailcraft avionics, solar panel arrays, and the communication antenna boom. The Science Bus contains all the science instruments, including the magnetometer boom, and the science instrument electronics. Each bus section has its own passive cooling system.

The connection between the Science Bus and Lower Bus is through a freely moving gimbal mechanism, with 3 degrees of freedom. Momentum wheels inside the Science Bus keep the science instruments pointed at the Sun to the required pointing accuracy and stability; when the momentum wheels are saturated, the gimbal mechanism is driven to the limit of the motion range to transfer momentum to the sail, to be de-saturated using the RCDs. The Science Bus is mounted at a nominal angle of 35.3 degree angle relative to the solar sail surface, corresponding to the optimal cone angle during the cranking phase of the mission.

The Spin-up Bus is a modified launch vehicle adapter and fulfils that function during launch. The bus also contains a propulsion system for initial attitude control and to spin up the sail during sail deployment. After the sail is deployed, the Spin-up Bus is jettisoned. To perform a safe jettison and disposal, the Spin-up Bus contains a simple controller and a bare minimum of navigation sensors (IMU and coarse sun sensor) which control the propulsion system to fly away from the sailcraft. The propulsion system is a blowdown hydrazine monopropellant system with 16 thrusters, each with 4N thrust and arranged into 4 pods of 4 thrusters each and located 1.75 m from the spacecraft centerline.

The total wet mass of the propulsion system is estimated to be 13.1 kg. However, because the Spin-Up Bus is not part of the sailcraft, the system may be replaced with a lower efficiency (higher mass) system, such as cold-gas thrusters, without affecting the sailcraft performance.

The HISM concept is based on the Solar Cruiser design concept. The sail for the Solar Cruiser mission is 1653 m^2 and provides a characteristic acceleration (Ac) of >0.12 mm/s^2. It uses a four quadrant sail design with four composite booms that are deployed from a central rotating deployment mechanism and sail hub.

The solar sail membrane is deployed and tensioned using four Triangular, Rollable, and Collapsible (TRAC) high strain composite (HSC) booms, the same geometry of the boom flight-validated by NanoSail-D2 and used on the upcoming NEAS mission. TRAC booms have a triangular cross section that flattens and rolls around a central spool for stowage. Deployment is actuated via a single motor controlled by the bus. This proven design has higher strength/weight for a given flattened height than other rollable boom designs [6] is easy to fabricate and taper, and has flight heritage.

The HISM sail is equipped with RCDs for attitude control, along with PE-PV generating power for the RCDs. Both technologies will be demonstrated on the Solar Cruiser, further advancing the solar sail architecture.

The sail membrane was assumed to be the same design as Solar Cruiser (2.5 micron CP1 substrate), and the sail system configuration was assumed to be the same as well, i.e. 4 sail quadrants supported by 4 tapered composite TRAC booms on a common spool for deployment. For a rigid or non-spinning sail system such as Solar Cruiser, each boom is under compressive stress from sail tension, and therefore the driving constraint for sizing of the system is the buckling of the booms. The tension requirement itself is derived from the stiffness requirement of the deployed system, i.e. maintaining a sufficiently high first mode natural frequency, as well as the flatness requirement of the sail membranes. As sail areas increase, the size and mass of the booms required to tension the sail become disproportionately large. To meet the HISM requirements, sail tension would need to be imparted using centrifugal force by spinning the sail at ~1 rpm. This centrifugal force reduces the buckling strength requirement of the composite TRAC booms, significantly decreasing their mass. Since the booms are no longer required for sail tension, their primary function then becomes providing out of plane stiffness to the sail membrane, improving sail flatness and reducing attitude control complexities experienced by other spinning sail missions such as IKAROS [7]. The resulting design achieves a 52 kg sail subsystem mass with a 7000m^2 sail area, including 4 booms, sail membranes, stowage spools, deployment mechanism, and 3 kg allowance for RCDs.

The GNC subsystem has some challenges for the HISM mission. The large sail and high spin rate lead to a large amount of angular momentum stored in the sail. This removes traditional attitude control actuators (RCS thrusters or reaction wheels) from the trade space for controlling the sail attitude. To do coarse steering of the vehicle, RCDs and active mass translator (AMT) were both studied for HISM.

RCDs are liquid-crystal devices that switch between transparent and translucent (diffuse) states based on the applied voltage. This principle has been successfully tested on the IKAROS mission [8] and is also currently under development for the Solar Cruiser. A set of 8 RCD panels, each with a 4.6 m^2 area and located at the outer corners of each sail quadrant, is baselined for the HISM design. This allows for 10^o/ day slew rate in the 0.48 AU orbit. Following the Solar Cruiser design, the RCDs are placed at an angle relative to the sail plane, allowing for roll torque to be generated by selectively turning on/off the RCDs. Each RCD is powered by sail-embedded PE-PV panels, currently under development at MSFC [9]. The PE-PV cells are located near the RCDs, along with a controller, to minimize cable mass and transmission loss. The controllers are commanded from a wireless transmitter in the sailcraft bus.

The AMT is a 2-axis translation mechanism that shifts the center of mass (CM) of the sailcraft bus relative to the center of pressure (CP) of the sail, generating a pitch or yaw torque. The baseline HISM design uses only RCDs for control of the sail; however, an AMT can be added if a decrease in RCD area is necessary or for redundancy in the system. A slew rate of 10^o/day is well within the capability of an AMT with ~21.5 cm motion range in each axis.

When the sail is deployed, the lower bus will be de-spun through a motor at the sail/bus interface. For attitude knowledge of the sail, the lower bus contains a coarse sun sensor and a star tracker. The science bus contains a star tracker and a more precise sun sensor for fine pointing and pointing knowledge of the science instruments. Three 0.10 NM reaction wheels are contained in the Science Bus to achieve the science instrument pointing requirements, using input from the fine sun sensor. An IMU is also be included for more accurate rate measurements.

HISM is launched on a dedicated launcher. With a launch mass of 358 kg and the requirement to be launched into a C3 > 0 trajectory, many existing launch vehicles are suitable for this mission. Shortly after the spacecraft (sailcraft + Spin-up Bus) is separated from the launcher, the thrusters in the Spin-up Bus are used to de-tumble the spacecraft and establish attitude control, and the solar arrays on the Lower Bus are deployed. The sail is then deployed, using the Spin-up Bus thrusters to increase the spin rate of the sail and ensure a sufficient spin rate to maintain the sail's structural integrity. After the sail is fully deployed, the Spin-up Bus disconnects from the sailcraft and uses the thrusters to fly away from the sail. The sailcraft then begins the inward spiral phase of the mission. The sailcraft remains in the ecliptic plane while it reduces the orbital radius from 1 AU to 0.48 AU.

Once a circular orbit is achieved at 0.48 AU, all science instruments will start continual operations. The sailcraft switches from spiralling to cranking operation, where the sail attitude is optimized for orbital inclination change. The orbit is a constant distance from the Sun, and the sail cone angle will also be held constant; only the sail clock angle (roll angle around the sailcraft-Sun line) will change. From this point on, the sailcraft continues to increase its orbital inclination. There is no defined end to the cranking phase; with no onboard consumables and assuming the sailcraft remains operational, it will eventually reach 90^o inclination. At this point the sailcraft may continue cranking past 90^o, or allow its orbital inclination to oscillate around 90^o.

4. Conclusions

A spacecraft in high inclination (>60^o) solar orbit, equipped with a combination of remote sensing and *in-situ* instrument, has the potential to dramatically change our understanding of the Sun and the heliosphere. The HISM concept study demonstrates the feasibility of such a mission using currently available components and technologies, and by using the solar sail technology currently under development for Solar Cruiser. The mission accommodates 46 kg of science instrument payload (60 kg with margin), including remote sensing instruments requiring 2 arcminute pointing accuracy and 7 arcsec/second stability. The sailcraft basic mass, estimated based on currently available components, is estimated at 240 kg, achieving a characteristic acceleration of 0.26 mm/s^2 which is sufficient to reach a 60^o inclination (heliographic) in 6.7 years from launch. Because the sailcraft has no on-board consumables, the maximum inclination and mission life are only limited by operations funding and longevity of the sailcraft components.

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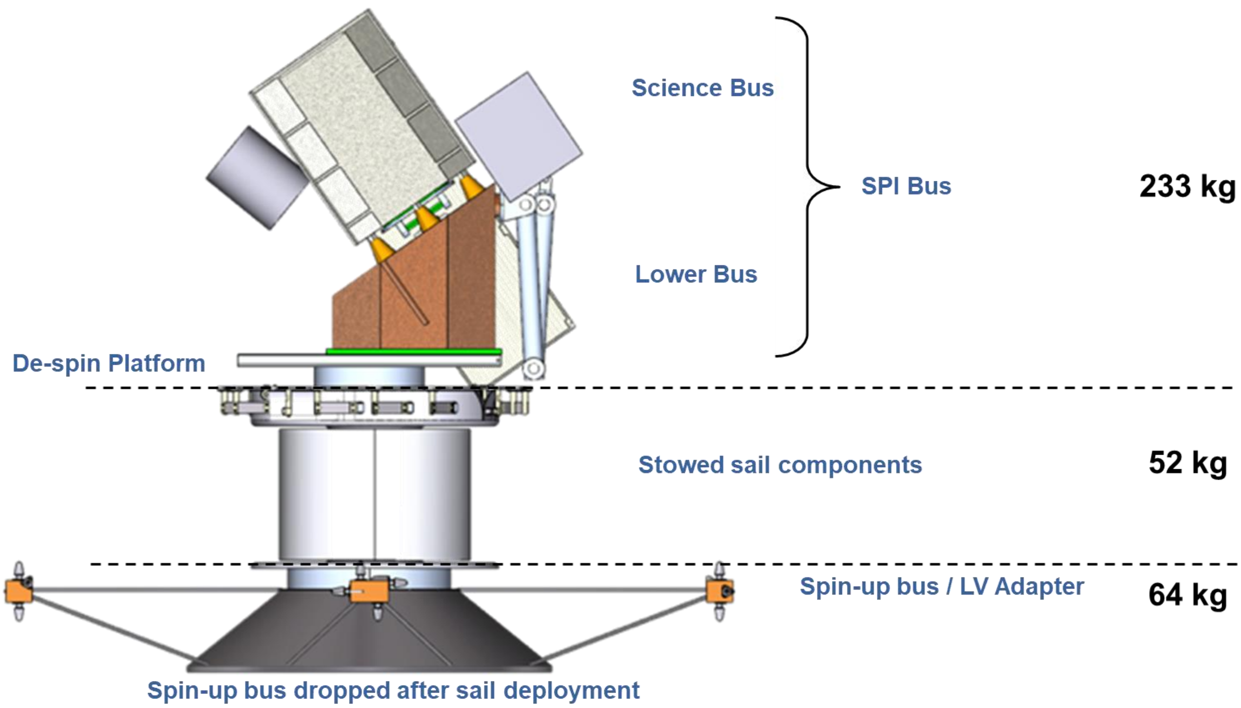

Figure 2. The HISM sailcraft mission concept showing the science bus and the separate, separable spin-up bus.